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SEDIMENTARY BASINS: TECTONIC RECORDERS OF SEDIMENT DISCHARGE FROM DRAINAGE CATCHMENTS

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ABSTRACT

The sedimentary basin is to geology what the drainage basin is to geomorphology, with sediment flux being a unifying link between the two features and disciplines. The global sediment discharge from continents to oceans contributes to major mass recycling associated with plate subduction. Major plate reorganization is accompanied by small fluctuations in continental volumes due to recycling of sediment stored along the sink-like passive margins. In continental sedimentary basins the SEdiment Preservation RAtio (SEPRA) depends upon the tectonic 'drawdown' of sediment flux preserved in the subsurface until basin inversion. Major unsteadiness in sediment discharge arises from tectonic or climatic causes, the latter prominent in the Quaternary to Holocene record. Contrasting trends in sediment discharge reflect both the nature of climate and vegetation change and source rock lithology. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

The major link between geomorphology and basin analysis is the sediment flux from catchment to basin. It is appropriate to extend Chorley's dictum concerning the primary role of the drainage catchment in geomorphological studies (Figure 1) to stand alongside a similar claim for the sedimentary basin in geology. It is the various controls (lithological, morphological, climatic and botanical) upon the magnitude of sediment flux that link the two subjects. These variables require the total sediment flux to be integrated over the whole range of the catchment (Figure 2), particulary when evaluating the effects of climate change.

Several authors have explored the consequences of variations in sediment discharge in models of basin stratigraphy, but in these the discharge is either considered implicitly via a variable deposition rate (Bridge and Leeder, 1979), varied as a transport coefficient (Flemings and Jordan, 1989), or considered explicitly for the transport-limited case with slowly varying changes in discharge (Paola *et al*., 1982). It is only recently that forward models of sediment production and erosion have allowed estimates of relative sediment yield. These are the Climate and Soil Erosion Potential (CSEP) models of Kirkby (1995) and Kirkby and Cox (1995). These consider that sediment discharge from catchment to basin is a function of two rates: soil production rate and soil transport rate. Both are controlled by precipitation through the production of vegetation and its role in the balance of water between evapotranspiration and runoff. The model curves provide a realistic test for previous empirical studies of the relationship between precipitation and sediment yield (e.g. Langbein and Schumm, 1958).

GLOBAL SEDIMENT DISCHARGE AND EARTH CYCLING

Estimates of past and present sediment discharge from the continents have clear relevance to the debate about earth cycling and the history of continental crustal growth. Mass balance estimates for continental growth rely largely upon comparison of rates of sediment subduction with geochemical, tectonic and magmatic additions estimated over tens or hundreds of millions of years (Reymer and Schubert, 1984; Von Heune and Scholl, 1991; Taylor and McLennan, 1995). Any variations in sediment supply with time to subduction zones is neglected in

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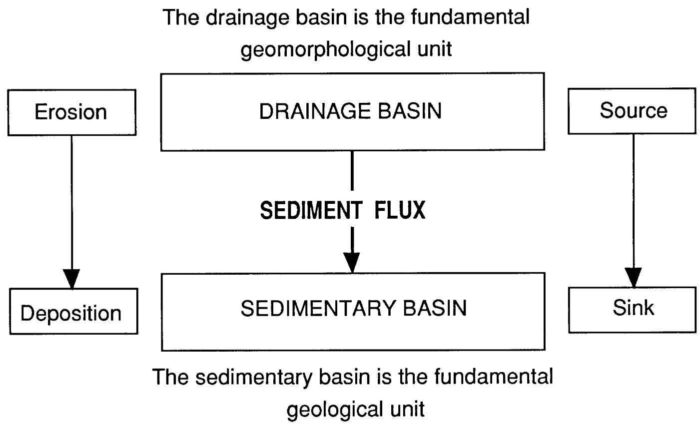

Figure 1. Concepts linking sedimentary basins and drainage basins (catchments), with acknowledgements for the latter to R. J. Chorley.

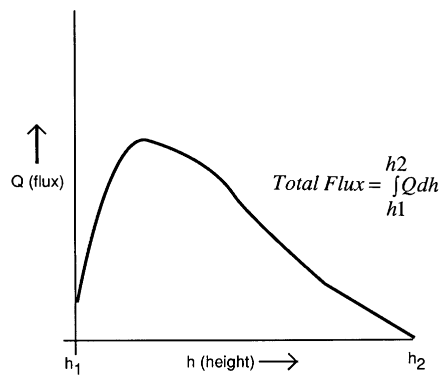

Figure 2. Indicative graph (arbitrary function) to show how the total sediment flux (and sediment production) from any catchment must be integrated over the altitudinal distribution in the catchment when considering catchment response to climate change.

these studies, as is the partitioning of deposited sediment between oceanic and continental crust. Estimates of pre-dam (*c.* AD 1900) Holocene sediment discharges seem to converge at around 8 $km^3\ a^{-1}$. Thus Milliman and Syvitski (1992) compute the pre-dam discharge at about 7·6 $km^3\ a^{-1}$. Summerfield and Hulton (1994) gathered data for major river systems draining some 35 per cent of the continental land area. Scaling up their discharge of about 2·6 $km^3\ a^{-1}$ gives a global figure of about 8·3 $km^3\ a^{-1}$.

Figure 3 indicates the magnitude of the annual global sediment discharge in comparison with published estimates of other magmatic and structural contributions to the continental crust. But is present-day sediment discharge a guide to past discharges of interest in longer term balancing studies? The answer commonly considers that we should be more interested in pre-farming (i.e. pre-Neolithic) or pre-Quaternary discharges for such comparisons. The former quantity is difficult to estimate. Judging from evidence of increased late Holocene sediment yields from the Aegean and elsewhere in the Mediterranean (e.g. Collier *et al*., 1995), the pre-farming discharge may have been as much as 50 per cent lower than the pre-dam flux. M. Summerfield (personal communication) has pointed out that this is likely to be a maximum estimate of uncertain validity world-wide, bearing in mind the dominance of a few very large tectonically active catchments in the delivery of sediment to the oceans. The pre-Quaternary discharge is impossible to estimate at present.

Concerning the partition of sediment discharge between continental and oceanic basins (Figure 4), it is clear that the majority of sediment is deposited in sedimentary basins and continental margins formed by stretching and thermal subsidence of the continental crust. Some proportion escapes the shelf and is deposited directly on ocean crust in submarine fans, as thermohaline ‘drifts’ and by mass-wasting processes from the steep slopes of

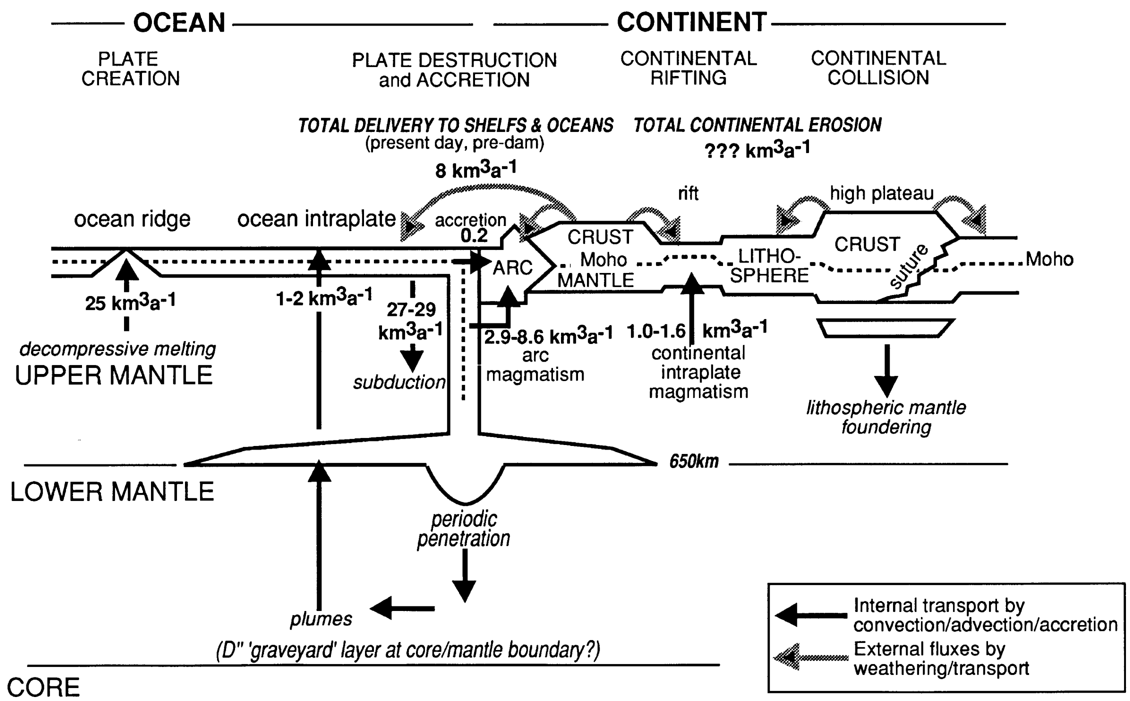

Figure 3. The magnitude of internal and external discharges from the earth's crust and mantle. Data for oceanic crustal mass balancing from Reymer and Schubert (1984) refer to mean Mesozoic–Cenozoic rates; but note that present-day rates are about 30 per cent less. Mean plume-transported basalt flux to the ocean crust (as both volcanics and plutonics) from White and McKenzie (1995); but note that the rates are highly unsteady. Estimates of mean Mesozoic–Cenozoic magmatic fluxes to the continents are from Crisp (1984); note that these are significantly higher than the 1·65 $km^3\,a^{-1}$ estimate of Reymer and Schubert (1984). The pre-dam modern sediment flux into the shelfs and oceans is from Milliman and Syvitski (1992); for discussion see text. See also Figure 4 for discussion of net crustal growth.

passive continental margins. It is this reservoir of sediments that is eventually transported on the subduction 'conveyor belt' when the margin turns destructive. Present-day major submarine fans comprise a volume of some 8×10^6 km^3 (Pickering *et al.*, 1989). Their ages are those of the major rivers supplying them and nowhere (apart from the Niger and Mississippi) does this exceed about 40 Ma. This gives a mean sediment discharge to the oceanic crust of about 0·2 km^3 a^{-1}, not including the contribution from contour drifts and mass-wasting. These latter can scarcely be more than the fan contribution, but their estimation awaits systematic study. We may 'guestimate' a likely maximum figure for the total sediment discharge to the ocean crust of about 0·5 km^3 a^{-1}.

Today, much of the discharge of sediment to the ocean crust (>90 per cent) occurs along passive oceanic margins and, although deposited on ocean crust, cannot begin to be partly digested into the mantle before the margins become destructive. Thus it seems that continental area must be periodically reduced by erosion and then enlarged by accretion as plate frameworks are adjusted on a time-scale of several hundred million years. It is possible that such long-term unsteadiness may help explain apparent correlation (Taylor and McLennan, 1995) of crustal growth with supercontinent accretion and dispersal cycles. However, given the magnitude of the oceanic sediment discharge compared with the total crustal volume (~8×10^9 km^3), the effect seems to be small (about 1 per cent over 100 Ma), but further work is required.

SEDIMENT PRESERVATION IN SEDIMENTARY BASINS

The magnitude of sediment discharge and its partition into transverse and axial components plays a major role in determining the stratigraphy of continental sedimentary basin fills (Figure 5). It is useful to develop the concept of SEdiment Preservation RAtio (SEPRA), defined as the ratio of mean annual sediment mass per unit

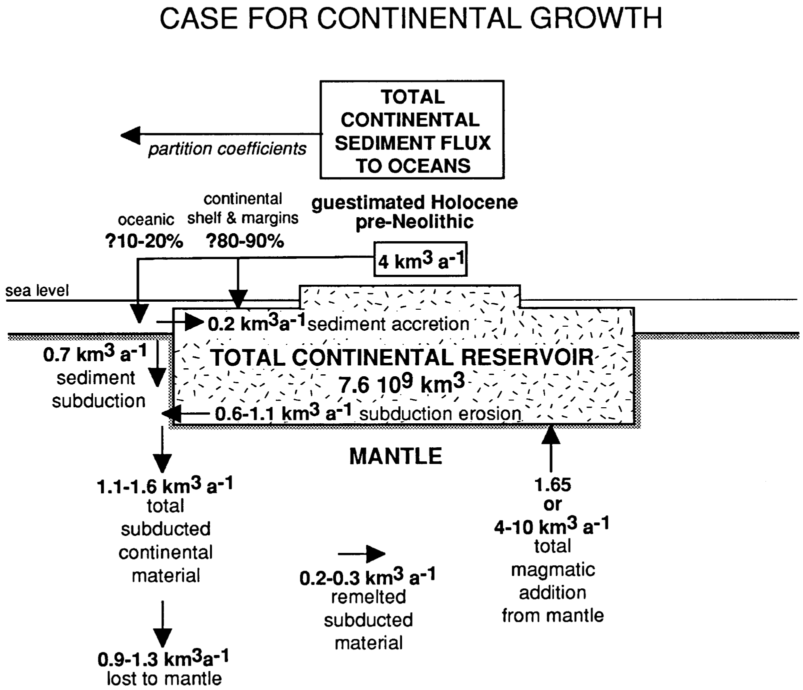

Figure 4. The fluxes relevant for determining continental crustal mass balances. It seems fair to 'guestimate' a maximum pre-Neolithic Holocene rate of sediment flux of about 50 per cent present day (pre-dam). Judging from the likely volume of submarine fan, thermohaline wedge and shelf-edge wasting contributions, less than 20 per cent of this may reach the subductable ocean crust. We have little knowledge of mean Mesozoic sediment flux rates to the oceanic crust but they are likely to have been lower, perhaps substantially so. Estimates of mean Mesozoic–Cenozoic accretionary prism sediment accretion, mean sediment subduction and subduction erosion rates are from Heune and Scholl (1991). The estimate of remelted subducted material flux is from Plank and Langmuir (1993). The quoted Mesozoic–Cenozoic magmatic fluxes are from Crisp (1984) and the Reymer and Schubert (1984) estimate, which is much lower ($1{\cdot}65\,km^3\,a^{-1}$). With Crisp's values there is net addition to the continents of some $2{\cdot}5$–$8{\cdot}0\,km^3\,a^{-1}$, but with Reymer and Schubert only $0{\cdot}35$–$0{\cdot}45\,km^3\,a^{-1}$. The causes of these large disparities clearly need further investigation.

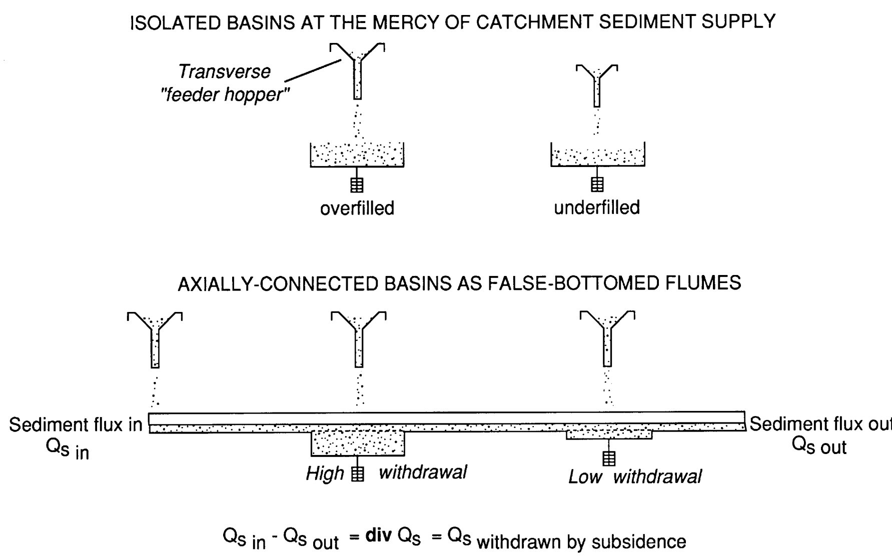

Figure 5. Cartoons to illustrate the concept of sediment preservation by tectonic withdrawal in isolated and axially connected alluvial basins (partly after Leeder *et al.*, 1996).

of basin floor preserved by tectonic subsidence to total mean annual mass per unit of basin floor transported through the basin. An analogue is a false-bottomed sediment flume (Figure 5) from which some proportion of the flux, Q_s, of downstream-transported sediment is drawn away by plungers, moving downwards at different speeds to simulate varying subsidence rates. SEPRA is basically an estimate of mass flux divergence (divQ_s) and should ideally be computed over the medium to long term (>10^3 years). SEPRA approaches unity in enclosed basins and ranges to zero in basins with no subsidence.

We may calculate various combinations of sediment flux and subsidence rate to arrive at estimates of SEPRA. For example, the Ganges–Brahmaputra alluvial basin is actively subsiding due to loading by the southward-thrusting Himalaya. The alluvial plains cover an area of some $2{\cdot}8\times10^3$ km^2; subsidence at an average rate of 1 mm a^{-1} over this area will preserve a sediment volume of some $2{\cdot}8\times10^{-3}$ km^3 a^{-1}. The modern Ganges–Brahmaputra rivers transport a total of some 0·76 km^3 a^{-1} of dissolved and suspended sediment load to the Bay of Bengal. Thus SEPRA for the modern basin is very low, at $2{\cdot}8\times10^{-3}/0{\cdot}76 = 0{\cdot}004$. We can also calculate SEPRA back to the middle Tertiary. Thus the volume of 'trapped' sediment preserved in the great marginal fans, Siwalik alluvium and subsurface Ganges–Brahmaputra alluvium has a volume exceeding $1{\cdot}0\times10^6$ km^3 (Johnson, 1993). If we compare this to the volume of the deposited sediment on the Bengal fan and Ganges–Brahmaputra delta (making an allowance for the likely magnitude of dissolved load at about 10 per cent of the suspended load), we see that the long-term SEPRA is around $1{\cdot}0\times10^6$ km^3/$1{\cdot}41\times10^7$ km^3 = 0·07. The low values of SEPRA attest to the great efficiency of the fluvial transport system in transporting suspended load to the oceans, despite the opposing trapping tendencies of the sedimentary basin, whose deposits include more coarse bedload.

UNSTEADY SEDIMENT DISCHARGE

Variations in sediment discharge with time are recognized from many sedimentary deposits in the young as well as the older geological record, and may be due to climatic and/or tectonic causes. The sedimentary basin is the chief means of the medium- to long-term preservation of the changing record. Correct reading of the stratigraphic record and the estimation of depositional volumes in basin sequences depends upon the establishment of an accurate chronology. In continental basins, reduced discharges are often indicated by the development of palaeosols which blanket formerly actively depositional areas. Tectonics is a major control on rates of sediment discharge through the effects of progressive uplift (Flemings and Jordan, 1989; Beaumont *et al*., 1992) and structural propagation (Leeder and Jackson, 1993; Jackson *et al*., 1996). This is particularly important where tectonics allows access to new catchment growth in soft young sediments, a common situation in tectonically active areas like the Mediterranean (Leeder *et al*., 1991).

Climatic modulation of sediment discharge at the eccentricity time-scale (~100 ka) has dominated the late Quaternary sedimentary record and probably played an important, though less well understood, control at precessional times-scales (~40 ka) in the late Pliocene and lower Pleistocene (Hilgen, 1991). There are many examples of the effects of climatic change in the Quaternary to Holocene sedimentary record (Bull, 1991) but only recently have comparative estimates of the accompanying change in sediment discharge (as distinct from deposition rate) been made (Collier *et al*., 1995). The chief control in semi-arid and Mediterranean climates is probably exerted through the complex relationship between mean annual temperature, precipitation and catchment vegetation, following the general lines of the CSEP model approach. Following the model of Bull (1991), vegetation is seen as both contributor to bedrock–sediment/soil transformation and as modulator of runoff and sediment erosion. Arboreal vegetation emerges as the key ecotype, with catchment forest cover at once generating deep soils and protecting them from erosion. Many studies (e.g. Brooks *et al*., 1994) have shown that removal of tree cover by human interference triggers runaway effects leading to increased sediment discharges. With sediment source areas stabilized under tree cover, depositional landforms in the basin must react. Fans develop widespread soil horizons surrounding incised channels, whilst axial rivers adjust their planform and floodplains to changed sediment and water discharges (e.g. Rose *et al.* 1980; Vandenberghe 1995).

The situation in high, rapidly uplifting mountain areas with very steep catchment slopes is more complex, with sediment discharges often very high, even with the presence of dense forest cover. Nevertheless, it must be

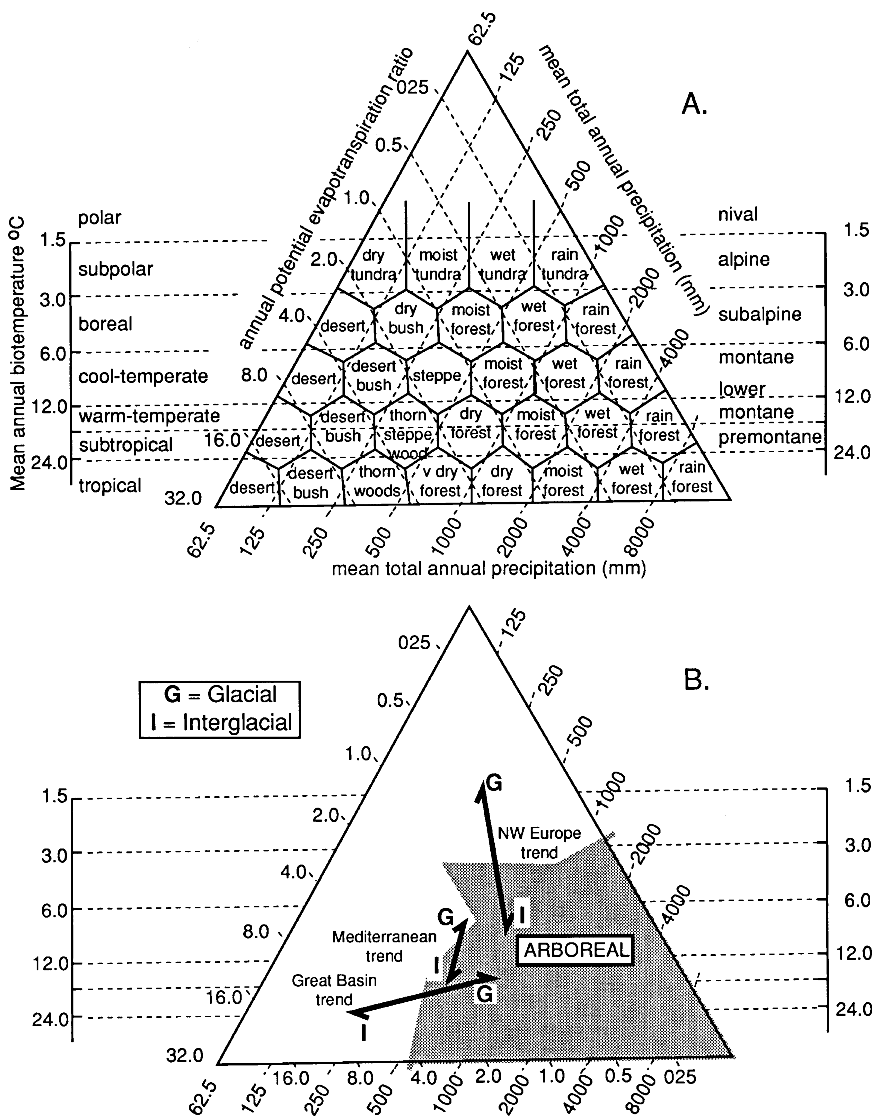

Figure 6. (A) Holdridge biome ternary plot (Prentice, 1990). (B) Trends expected for glacial to interglacial changes appropriate to low elevations in temperate latitudes of the Mediterranean and the Great Basin of the western USA. In all three cases, the trend from arboreal to non-arboreal vegetation signifies an increased (though probably transiently so) sediment yield.

admitted that removal of the tree cover would increase these discharges even more.

Use of a simplified Holdridge plot (Figure 6) enables us to see that replacement of tree cover may take place due to a change in temperature and/or precipitation. In modern temperate climates, the various changes accompanying deglaciation are now widely understood to have caused major decreases in sediment availability in the transition from late-Pleistocene to Holocene times. This has manifested itself in the form of river channel changes and terrace cutting, providing instructive insight into the dynamics of the fluvial system. We also contrast here the behaviour of depositional systems in the northern Great Basin of the western USA with those in the Mediterranean. In the former area, particularly Nevada/E California, wetter and cooler pre- Holocene climate enabled catchment tree cover and soil formation to develop with a virtual shutdown of fan deposition and development of thick draping soils (Reheis *et al.*, 1996). The Holocene trend to higher temperatures, aridity and dominance of summer convective precipitation events has caused tree cover to reduce or disappear and the incidence of debris flow deposition to increase. This contrasts markedly with the situation in the late Quaternary

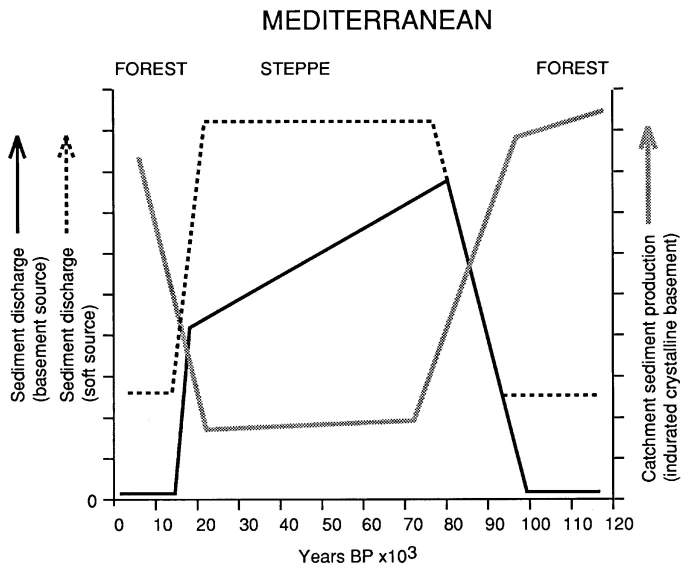

Figure 7. Indicative graphs of sediment yield for glacial and interglacial time in Mediterranean localities having 'hard' and 'soft' rock types. Note that 'soft' rock substrates are always transport-limited wrt sediment yields which should therefore increase during the periods of higher runoff experienced during glacial (steppe) intervals when trees are absent (see Figure 5). By way of contrast, 'hard' rock substrates depend upon arboreal vegetation to weather them, to create soil *and* to protect the developing soil profile from erosion. They are expected to show peak sediment yields soon after initiation of glacial steppe conditions as the trees die away and the deep precursor soils are eroded. These transient conditions subsequently become soil-production-limited until the next cycle of tree growth, deep soil formation and so on.. Graph stops pre-Bronze Age.

of the northern Mediterranean. Here, evidence for Mediterranean climate change strongly suggests that glacial maxima have been characterized by widespread development of treeless steppe with increased winter runoff and high lake levels (Prentice *et al.*, 1992; Tzedakis, 1993). We may postulate (Figure 7) that these precipitation, temperature and vegetational changes were the cause of the widespread pre-Holocene deposition evident on many alluvial fans (Harvey, 1990, 1992; Leeder *et al.*, 1991; Nemec and Postma, 1993). Climate change since 14 ka slowly established the natural Mediterranean woodland ecotype once more (Rossignol-Strick and Planchais, 1989) and stabilized many alluvial fans. Human forest clearance from Bronze Age times has caused sediment flux to increase once more in many areas (see papers in Bottema *et al.* (1990) and Lewin *et al.* (1995).

The geologically rapid climatic changes of the Quaternary raise serious problems for the determination of long-term sediment flux and denudation rates. These need to be integrated over time-spans well in excess of 100 ka and to take account of the effects of catchment relief and vegetation zones (Figure 8). Opportunities for integration arise in the northern Great Basin where alluvial fan accumulations overlie volcanic datum planes of known age (Beaty, 1970; Leeder, 1991). Simple structural dips of the tilted volcanics then enable extrapolated volumes to be calculated, which may then be used to determine sediment discharge and denudation rates. A good example in the White Mountains of eastern California is Milner Creek fan, which overlies the well-dated 700 ka Bishops Tuff erupted from Long Valley caldera. Beaty (1970) has previously established the fan volume to be some 1·73 km^3, giving a mean late-Quaternary sediment discharge from catchment to fan of some 2460 m^3 a^{-1}. In terms of the 1952 'typical' debris flow event of volume $8{\cdot}7\times10^5$ m^3, Beaty calculated that one such event every 350 years would suffice to construct the whole fan. I calculate the mean denudation rate for the whole 35·5 km^2 Milner Creek catchment over the past 700 ka as around 0·06 mm a^{-1}, after allowance for sediment porosity but neglecting chemical denudation and any contribution to axial sediment flux. This long-term mean value must be related to the detailed studies of fan architecture and stratigraphy presented by authors such as Reheis *et al.* (1997) from adjacent fans. As noted previously, such studies indicate severe long-term unsteadiness in sediment discharge rates such that for perhaps the majority of pluvial/glacial periods over the lifetime of Milner Creek fan (the majority of the fan's lifetime?), there was very little sediment discharge

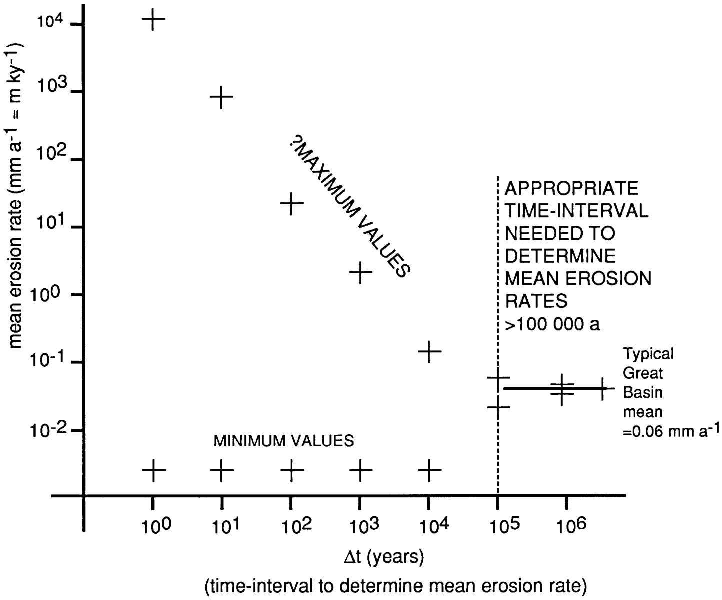

Figure 8. Graph to show how notional estimates of maximum and minimum erosion rates might converge towards a long-term mean at time intervals >100 ka. Data from Great Basin (California White Mountains), discussed in text.

indeed: the implication is that discharges in warmer, more arid interglacials must have been very much higher. Regardless of the ‘unreality’ of the long-term rate estimates, these are vital parameters in longer term erosional models such as CSEP. Indeed, the particular value derived from the Milner fan is similar to many other such long-term estimates from the Great Basin and Rio Grande rift (e.g. Dethier *et al*., 1988; Leeder, 1991).

CONCLUSIONS

Understanding and predicting the magnitude of sediment discharge from catchment to sedimentary basin remains the goal of quantitative geomorphologists and basin analysts alike. A major problem is the unsteadiness in sediment discharge arising from tectonic or climatic causes. Climate change or tectonic uplift of young soft sediments is difficult to model in terms of soil erosion potential since transients become important. Thus weathering-limited conditions change rapidly to transport-limited with the disappearance of tree cover, but once eroded, the thick soils are difficult to replace until climate changes once more. Uplift of young soft or multilayered soft/hard sediments provides a major opportunity for increased sediment erosion throughout the period of changed or changing climate.

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